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Soldi et al.

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(54) **METHOD FOR ROUGHNESS REDUCTION IN MANUFACTURING OPTICAL DEVICE STRUCTURES**

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F21V 8/00	(2006.01)
G02B 5/18	(2006.01)

(52) **U.S. Cl.**

CPC ***G02B 6/0065*** (2013.01); ***G02B 5/1857*** (2013.01); *G02B 6/0016* (2013.01); *G02B 6/0036* (2013.01)

(58) **Field of Classification Search**

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See application file for complete search history.

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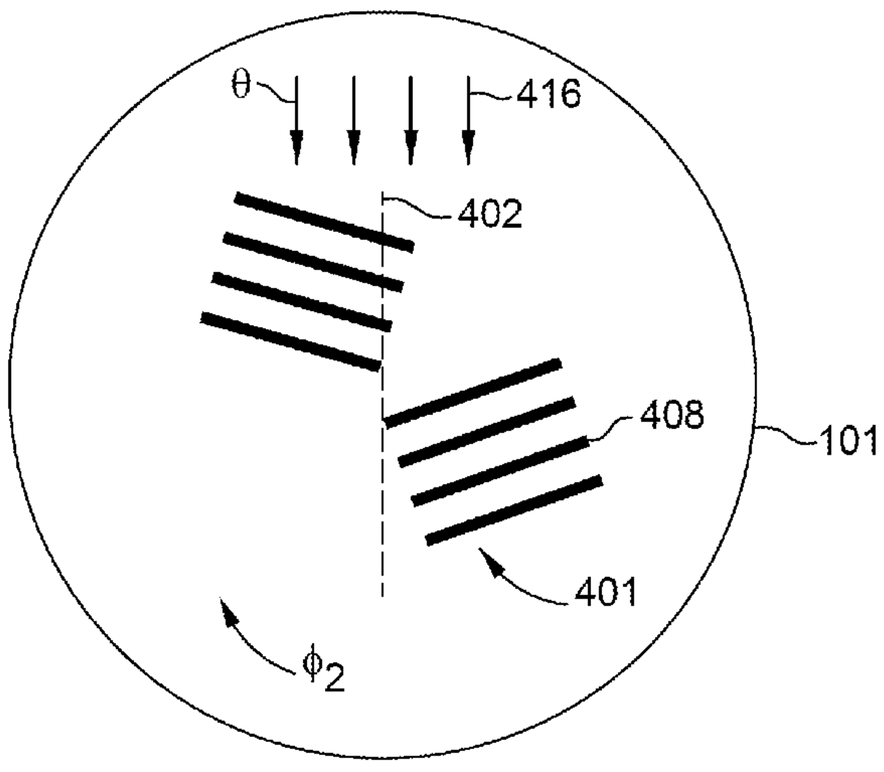
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(57) **ABSTRACT**

Embodiments described herein relate to a method of using an apparatus for forming waveguides. The method includes positioning a substrate at a first rotation angle, exposing the substrate to an ion beam, forming first partial trenches defined by adjacent angled device structures with the first device angle, rotating the substrate to a second rotation angle, exposing the substrate to the ion beam, etching the first partial trenches, and repeating the method from about 1 cycle to about 100 cycles to form a plurality of trenches defined by adjacent angled device structures. The first rotation angle is selected to form one or more angled device structures with a first device angle relative to a vector parallel to the substrate. The ion beam is configured to contact the substrate at a beam angle ϑ relative to a surface normal of the substrate.

20 Claims, 5 Drawing Sheets



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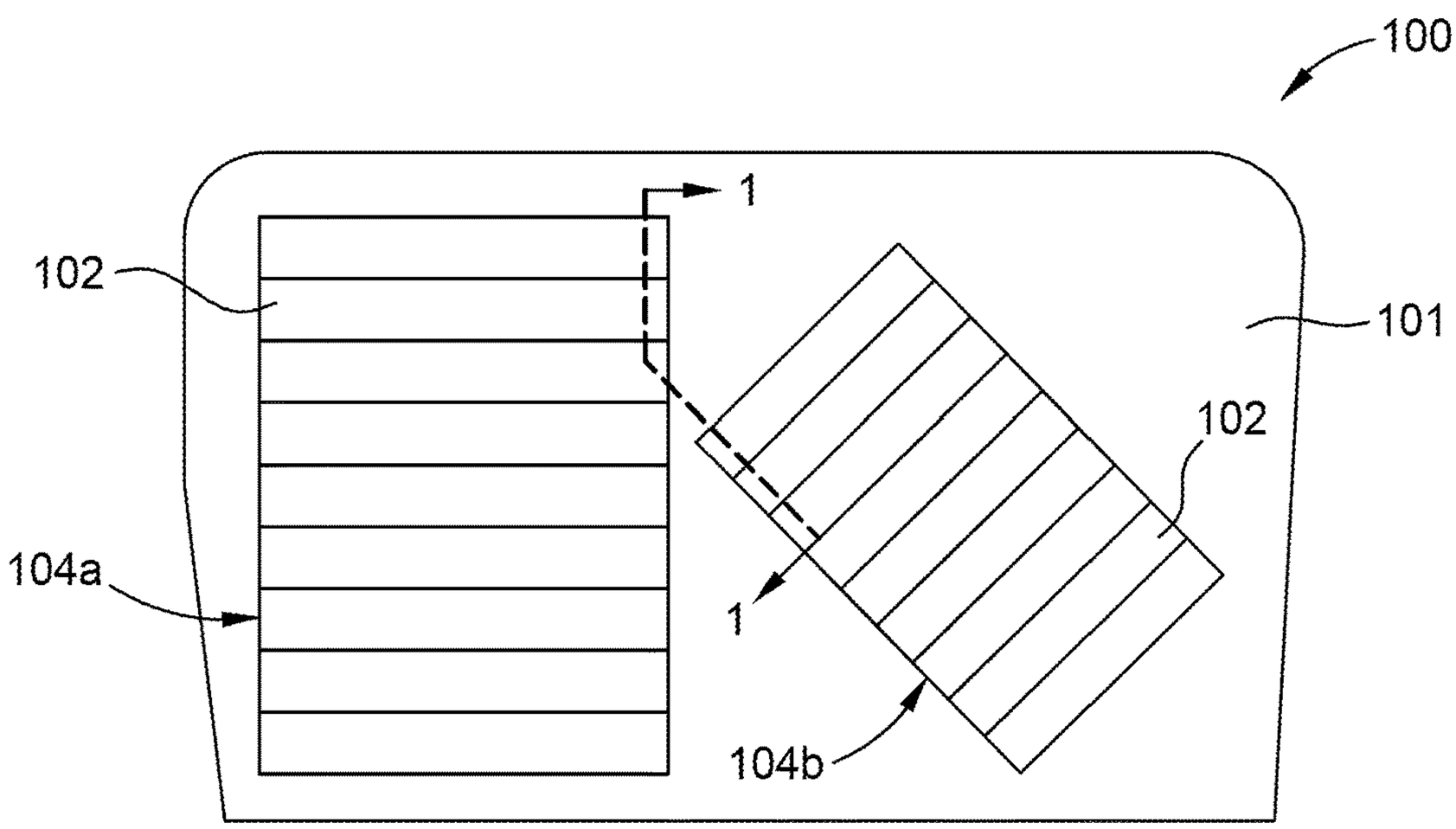


FIG. 1A

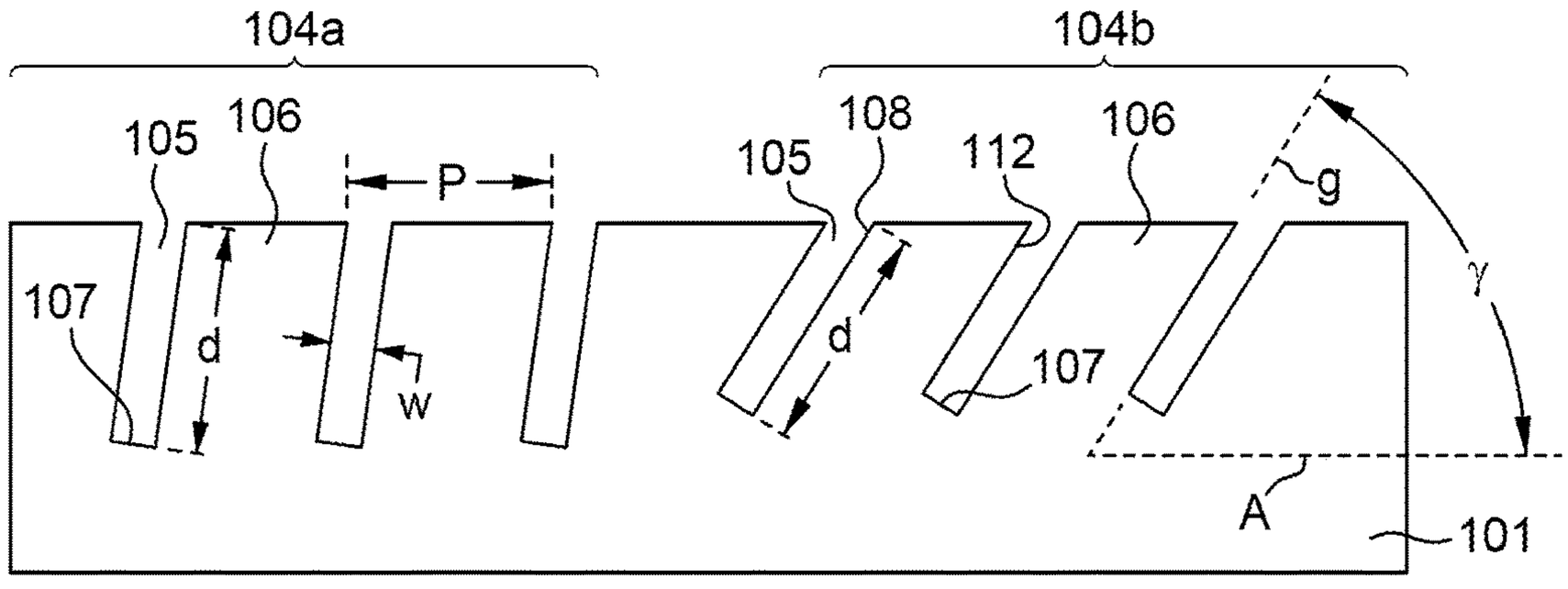


FIG. 1B

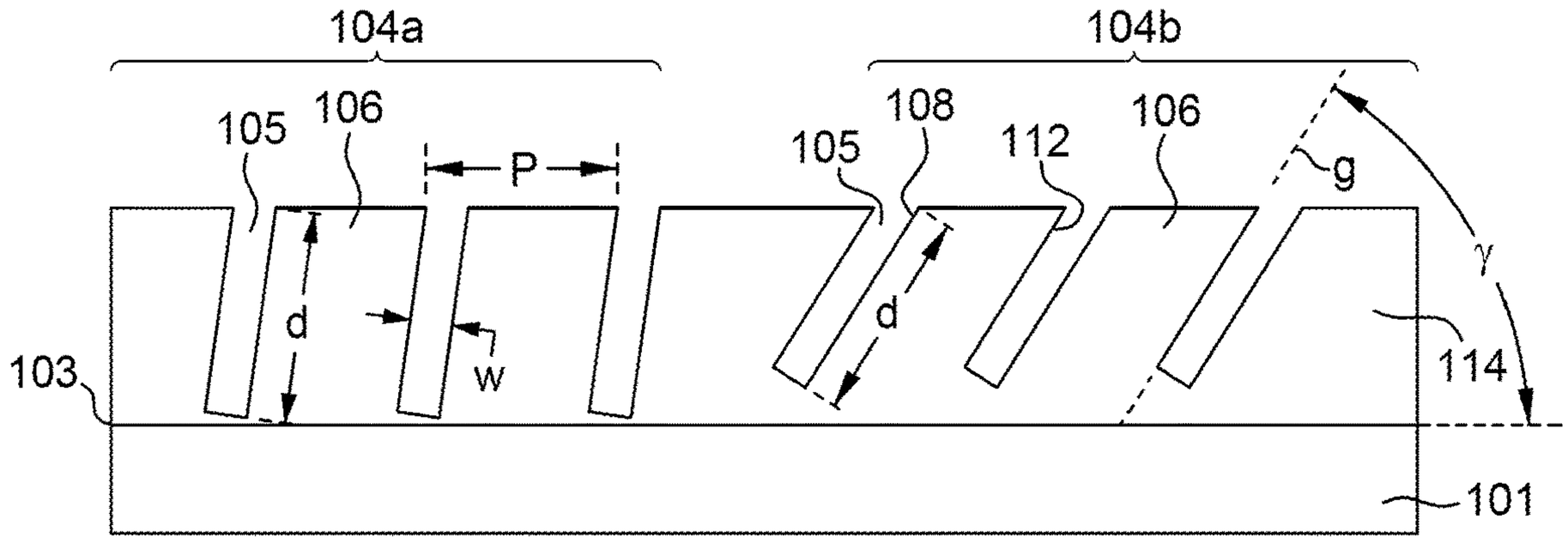


FIG. 1C

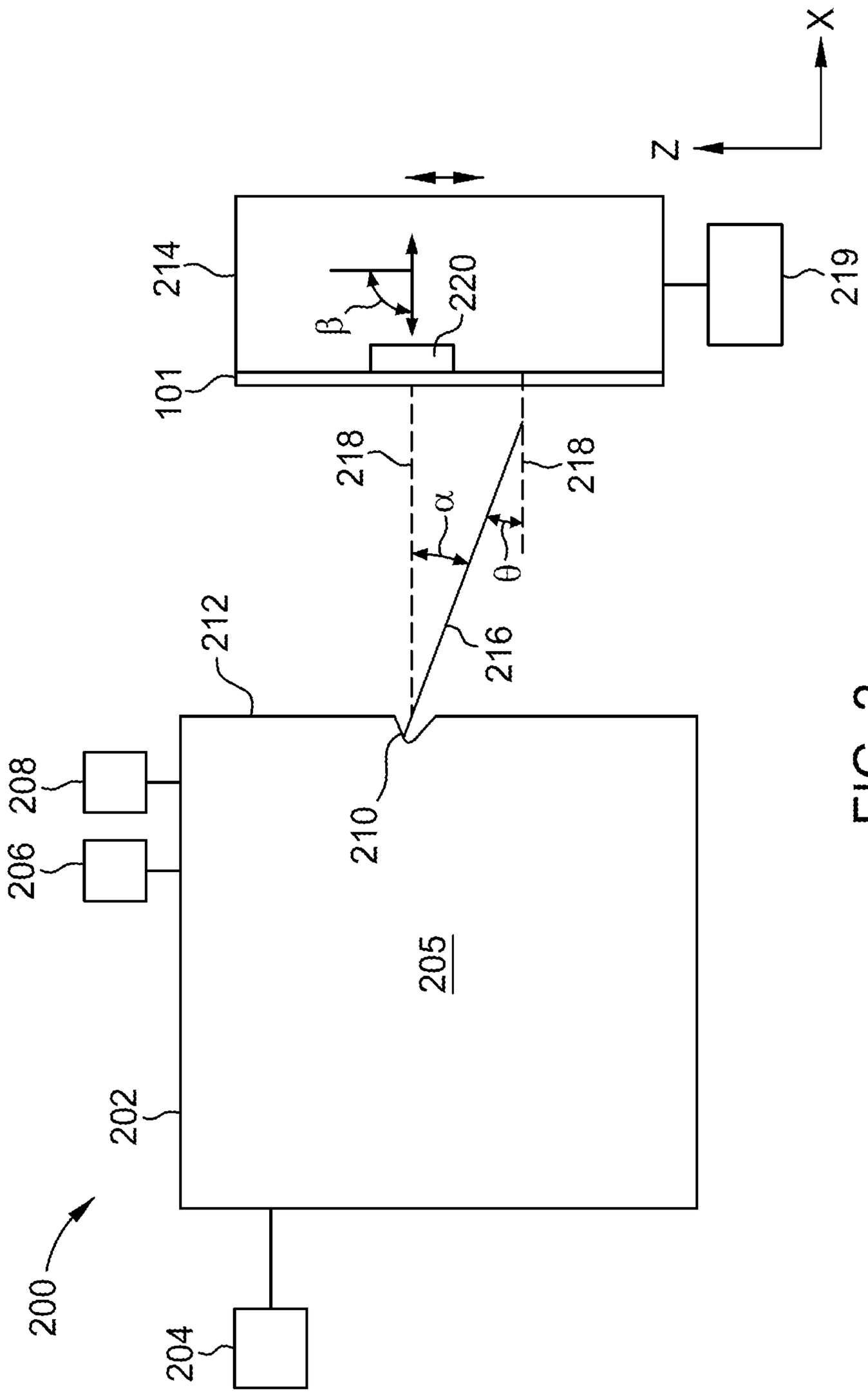

X
Z
214
β
220
219
101
218
218
α
θ
212
216
210
208
206
205
202
200
204

FIG. 2

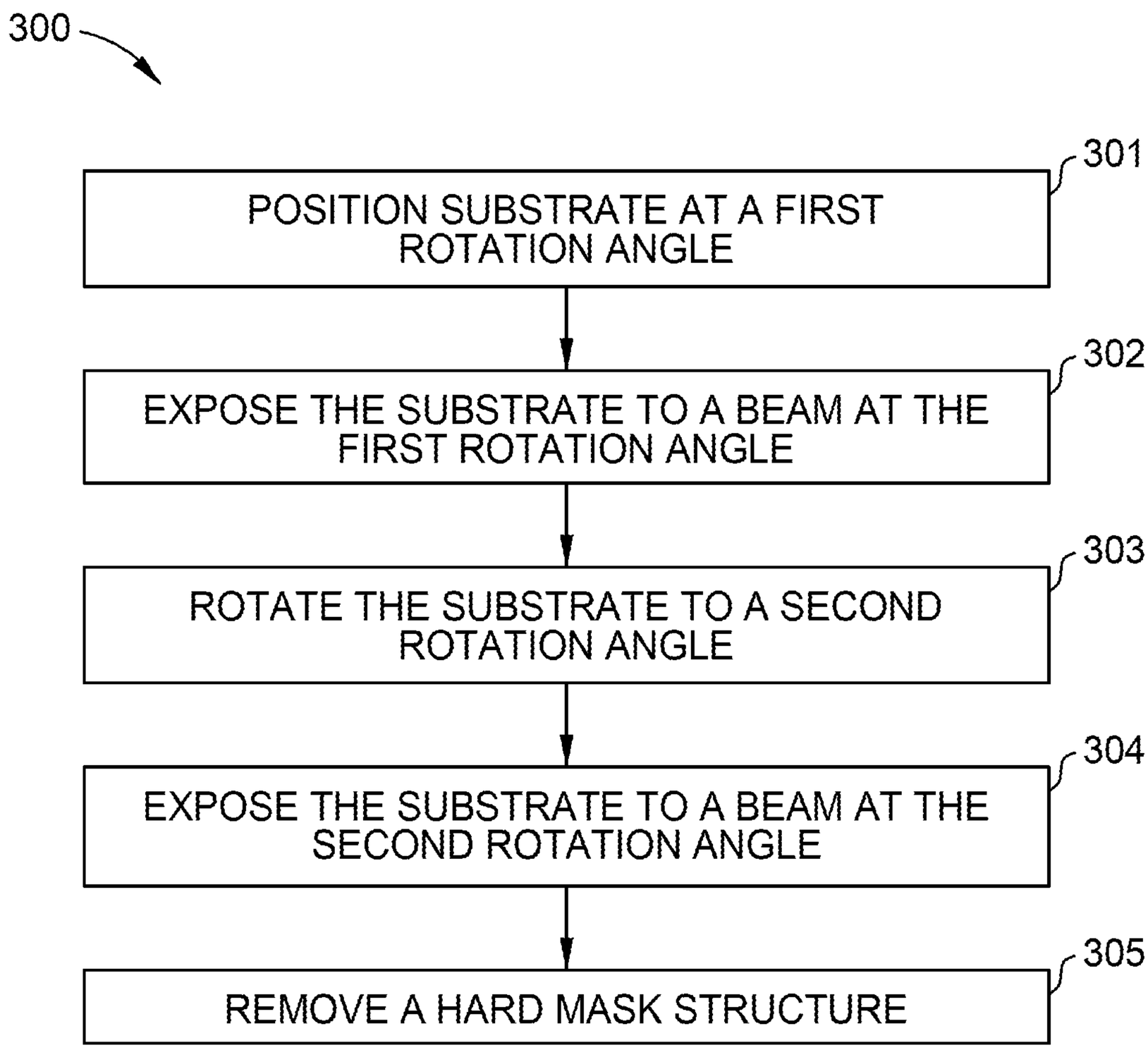

300
POSITION SUBSTRATE AT A FIRST ROTATION ANGLE
301
EXPOSE THE SUBSTRATE TO A BEAM AT THE FIRST ROTATION ANGLE
302
ROTATE THE SUBSTRATE TO A SECOND ROTATION ANGLE
303
EXPOSE THE SUBSTRATE TO A BEAM AT THE SECOND ROTATION ANGLE
304
REMOVE A HARD MASK STRUCTURE
305

FIG. 3

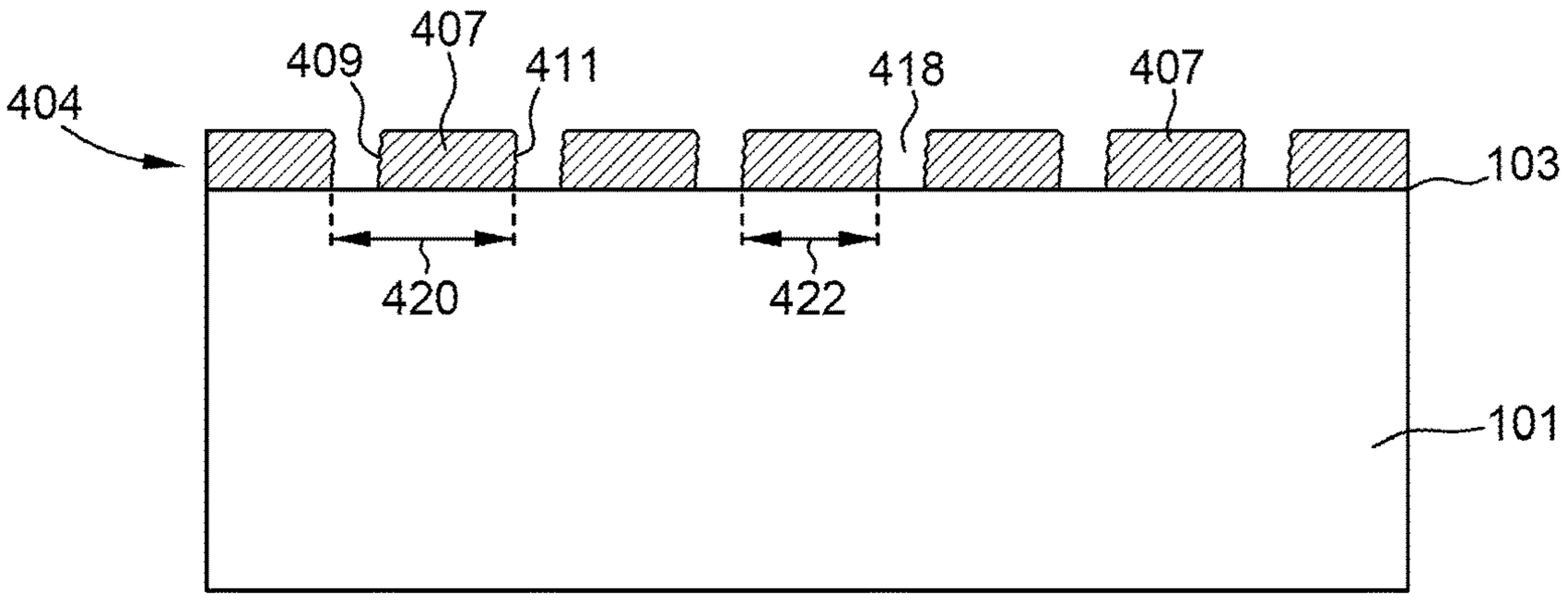


FIG. 4A

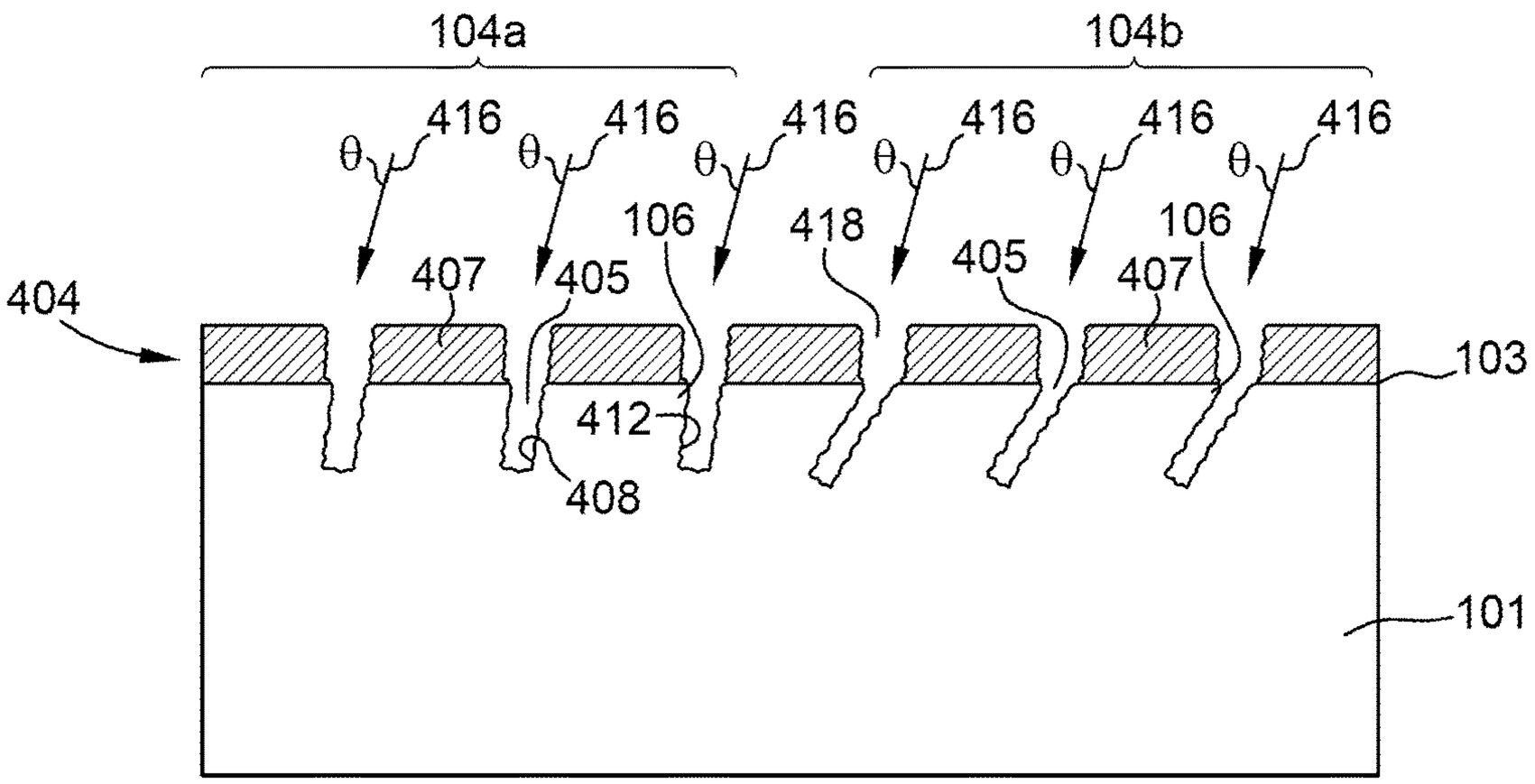


FIG. 4B

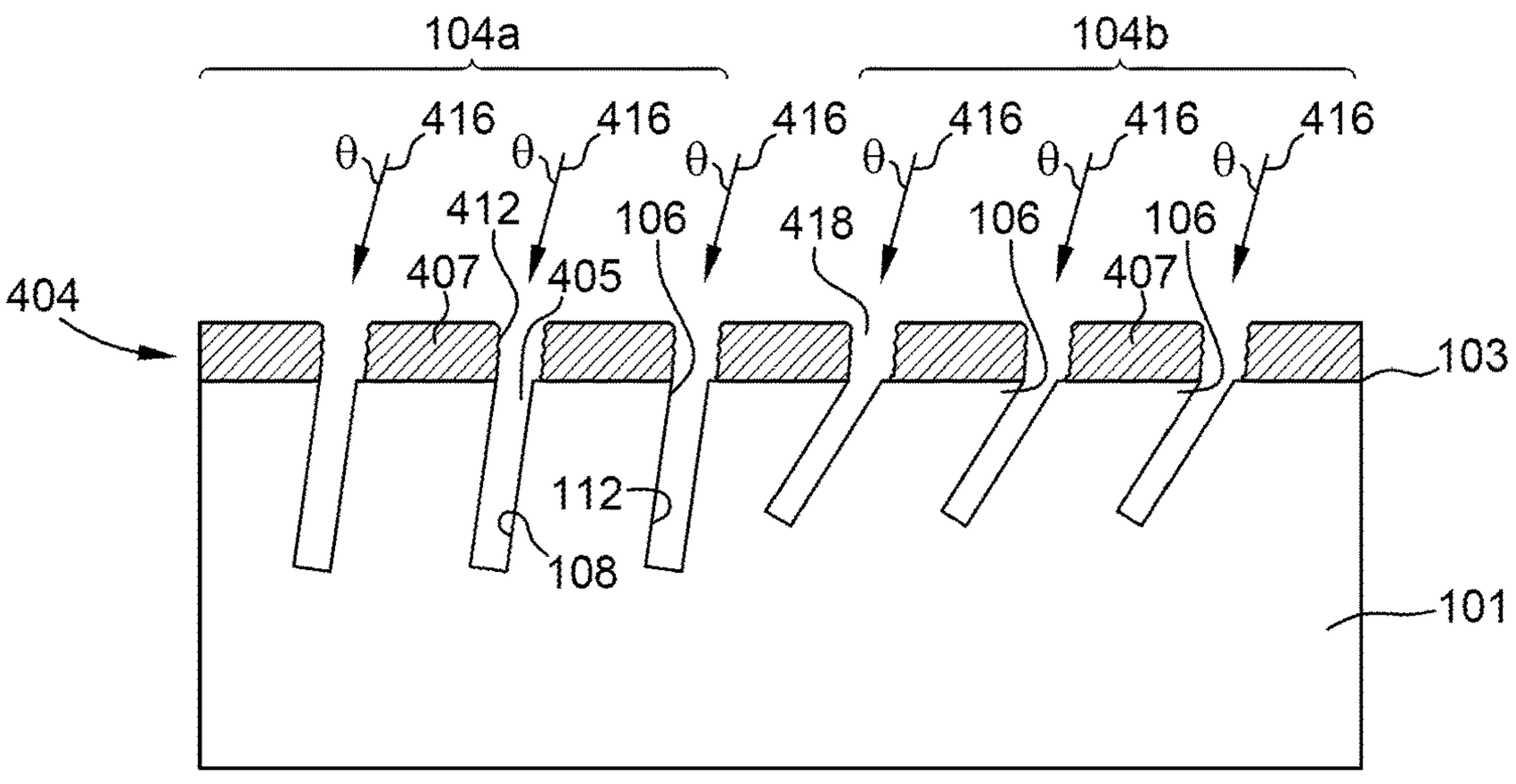


FIG. 4C

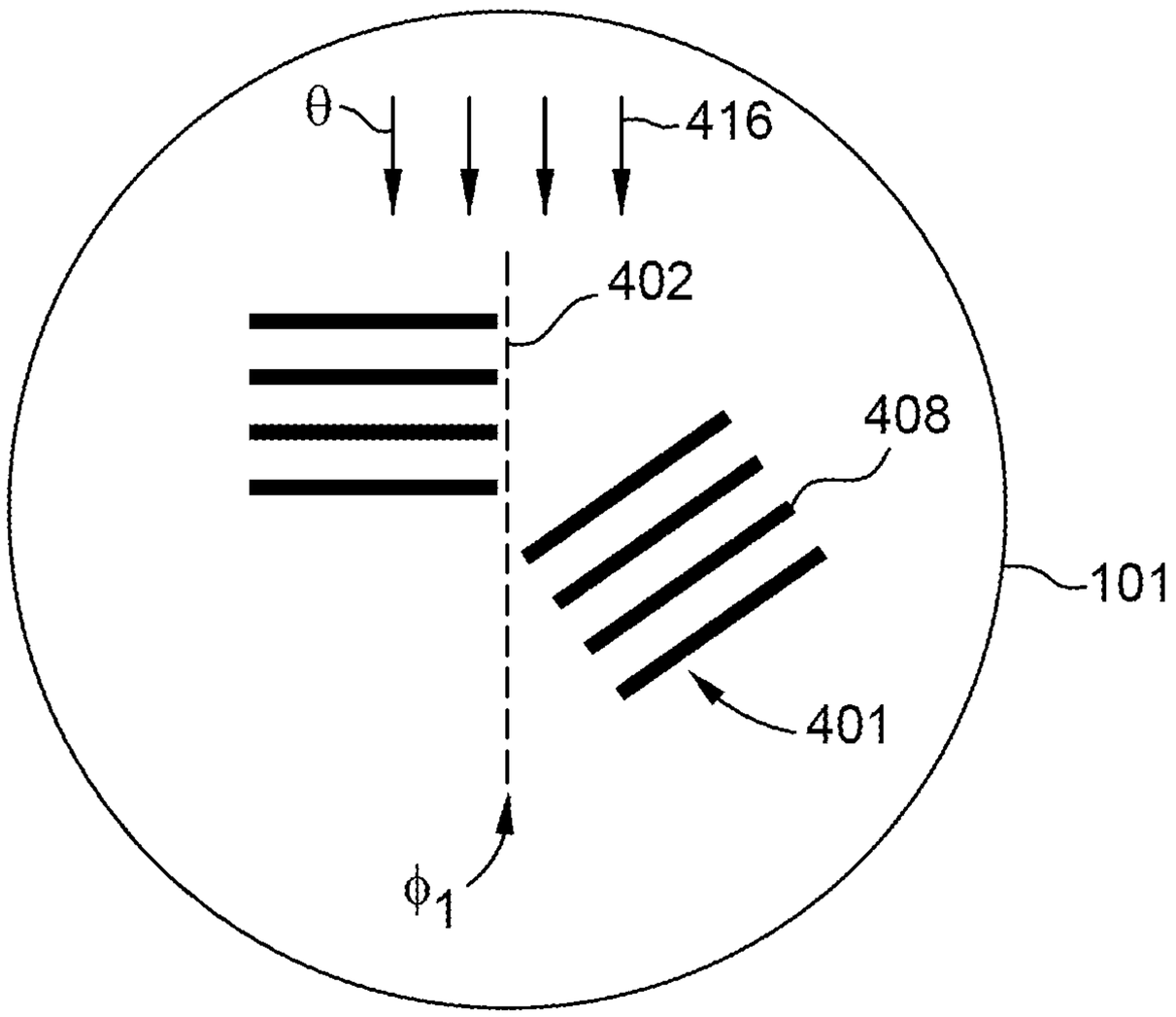


FIG. 4D

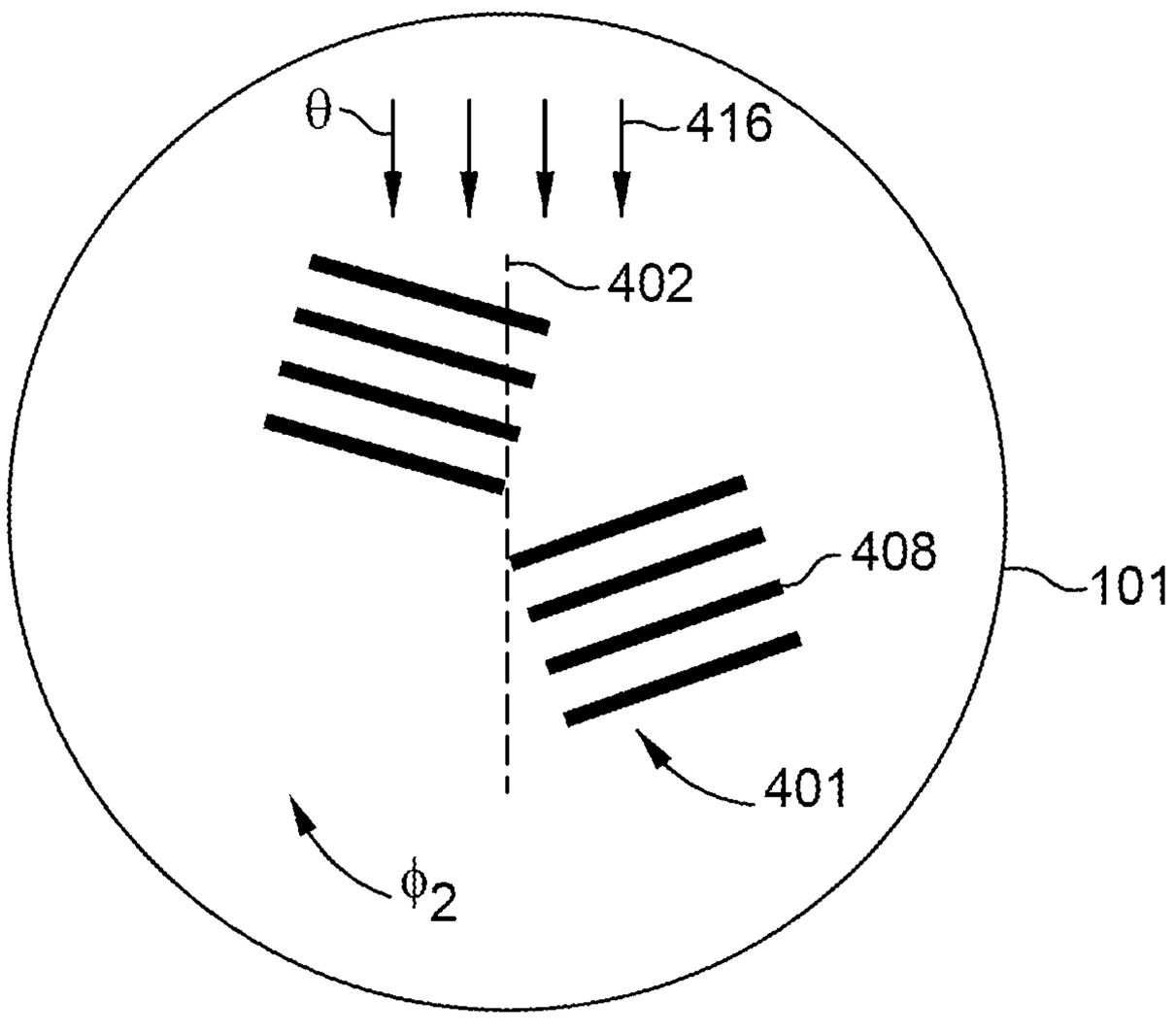


FIG. 4E

METHOD FOR ROUGHNESS REDUCTION IN MANUFACTURING OPTICAL DEVICE STRUCTURES

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. provisional patent application Ser. No. 63/333,071, filed Apr. 20, 2022, which is herein incorporated by reference.

BACKGROUND

Field

Embodiments of the present disclosure generally relate to waveguides for augmented, virtual, and mixed reality. More specifically, embodiments described herein provide for forming waveguide structures.

Description of the Related Art

Virtual reality is generally considered to be a computer generated simulated environment in which a user has an apparent physical presence. A virtual reality experience can be generated in 3D and viewed with a head-mounted display (HMD), such as glasses or other wearable display devices that have near-eye display panels as lenses to display a virtual reality environment that replaces an actual environment.

Augmented reality, however, enables an experience in which a user can still see through the display lenses of the glasses or other HMD device to view the surrounding environment, yet also see images of virtual objects that are generated for display and appear as part of the environment. Augmented reality can include any type of input, such as audio and haptic inputs, as well as virtual images, graphics, and video that enhance or augment the environment that the user experiences. As an emerging technology, there are many challenges and design constraints with augmented reality.

One such challenge is displaying a virtual image overlaid on an ambient environment. Waveguides are used to assist in overlaying images. Generated light is propagated through a waveguide until the light exits the waveguide and is overlaid on the ambient environment. Waveguides may require structures having angles relative to the surface of the optical device substrate.

Accordingly, what is needed in the art are improved methods of forming optical devices including angled device structures with angled etch tools.

SUMMARY

In one embodiment, a method is provided. The method includes positioning a substrate at a first rotation angle, exposing the substrate to an ion beam, forming first partial trenches defined by adjacent angled device structures with the first device angle, rotating the substrate to a second rotation angle, exposing the substrate to the ion beam, etching the first partial trenches, and repeating the method from about 1 cycle to about 100 cycles to form a plurality of trenches defined by adjacent angled device structures. The first rotation angle is selected to form one or more angled device structures with a first device angle relative to a vector parallel to the substrate. The ion beam is configured to contact the substrate at a beam angle θ relative to a surface normal of the substrate. The second rotation angle is from about −20° to about 20°.

In another embodiment, a method is provided. The method includes positioning a substrate at a first rotation angle, exposing the substrate to an ion beam, forming a partial trench defined by adjacent angled device structures, rotating the substrate to a second rotation angle, exposing the substrate to the ion beam, etching the partial trench, rotating the substrate to a third rotation angle, exposing the substrate to the ion beam, etching the partial trench, and repeating the method from about 1 cycle to about 100 cycles to form a plurality of trenches defined by adjacent angled device structures. The first rotation angle is selected to form one or more angled device structures with a first angle relative to a vector parallel to the substrate. The ion beam is configured to contact the substrate at a beam angle θ relative to a surface normal of the substrate. The partial trench has a first sidewall and a second sidewall. The second rotation angle is from about −20° to about 20°. The third rotation angle is from about −20° to about 20.

In yet another embodiment, a method is provided. The method includes positioning a substrate at a first rotation angle, exposing the substrate to an ion beam, forming a trench defined by adjacent angled device structures, rotating the substrate to a second rotation angle, exposing the substrate to the ion beam, and removing the hard mask structures. The first rotation angle is selected to form one or more angled device structures with a first angle relative to a vector parallel to the substrate. The substrate has a patterned resist disposed thereon. The patterned resist includes a plurality of hard mask structures and one or more gaps. Each of the hard mask structures has a width. Each of the gaps is defined by adjacent hard mask structures. The ion beam is configured to contact the substrate at a beam angle θ relative to a surface normal of the substrate. The trench has a first sidewall and a second sidewall. The trench is formed using the ion beam having a substrate etch chemistry to remove the substrate. The second rotation angle is from about −20° to about 20°. The hard mask structures are removed by the ion beam generated by a hard mask etch chemistry different than the substrate etch chemistry.

BRIEF DESCRIPTION OF THE DRAWINGS

So that the manner in which the above recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only exemplary embodiments of the disclosure and are therefore not to be considered limiting of its scope, and may admit to other equally effective embodiments.

FIG. **1**A is a perspective, frontal view of a waveguide according to embodiments described herein.

FIG. **1**B are schematic, cross-sectional views of a portion of a waveguide according to embodiments described herein.

FIG. **1**C are schematic, cross-sectional views of a portion of a waveguide according to embodiments described herein.

FIG. **2** is a schematic, side view of an angled etch system according to embodiments described herein.

FIG. **3** is a flow diagram of a method for forming a waveguide according to embodiments described herein.

FIG. **4**A-**4**C are schematic, cross sectional views of a substrate during a method according to embodiments described herein

FIGS. **4**D-**4**E are schematic, top views of a substrate during a method according to embodiments described herein.

To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. It is contemplated that elements and features of one embodiment may be beneficially incorporated in other embodiments without further recitation.

DETAILED DESCRIPTION

Embodiments of the present invention generally relate to waveguides for augmented, virtual, and mixed reality. More specifically, embodiments described herein provide for methods of forming waveguide structures.

FIG. **1**A illustrates a perspective, frontal view of a waveguide **100**. It is to be understood that the waveguide **100** described below is an exemplary waveguide. The waveguide **100** includes a plurality of device structures **102** disposed in (as shown in FIG. **1**B) or on (as shown in FIG. **1**C) a substrate **101**. As shown in FIG. **1**C, the device structures **102** are formed in a device layer **114** formed on the substrate **101**. The device structures **102** may be nanostructures having sub-micron dimensions, e.g., nano-sized dimensions, such as critical dimensions less than 1 μm. In one embodiment, which can be combined with other embodiments described herein, regions of the device structures **102** correspond to one or more gratings, such as a first grating **104***a* and a second grating **104***b*. In one embodiment, which can be combined with other embodiments described herein, the waveguide **100** is a waveguide combiner that includes at least the first grating **104***a* corresponding to an input coupling grating and the second grating **104***b* corresponding to an output coupling grating. The waveguide combiner according to the embodiment, which can be combined with other embodiments described herein, may include an additional grating corresponding to an intermediate grating.

FIG. **1**B is a schematic, cross-sectional view of a portion of a waveguide **100** at section-line **1-1**. FIG. **1**C is a schematic, cross-sectional view of a portion of a waveguide **100** at section-line **1-1**. In one embodiment, which can be combined with other embodiments described herein, the device structures **102** are angled device structures **106** of a flat waveguide, such as a metasurface. The method **300** described herein with reference to FIG. **3** forms the angled device structures **106**. In another embodiment, which can be combined with other embodiments described herein, the device structures **102** are angled device structures **106** of a waveguide combiner, such as an augmented reality waveguide combiner. The waveguide combiner, which can be combined with other embodiments described herein, may include angled device structures **106** in at least one of the gratings **104**. Each of the angled device structures **106** includes a first sidewall **108**, a second sidewall **112**, and a pitch p. The angled device structure **106** (e.g., the first sidewall **108** and second sidewall **112**) has a device angle γ. The device angle γ is the angle between a grating vector g and a parallel vector A. The grating vector g is a vector of the first sidewall **108** or the second sidewall **112**. The parallel vector A is a vector parallel to a top surface **103** of the substrate **101**. The device angle γ may be between about 0° to about 80°. The pitch p corresponds to the distances between first sidewalls **108** of adjacent angled device structures **106**.

Adjacent angled device structures **106** define trenches **105**. The trenches **105** have a depth d and a width w. In FIG. **1**B, the depth d of a trench **105** is the distance from the top surface of the substrate **101** to the deepest point of the trench **105**. In FIG. **1**C, the depth d of a trench **105** is the distance from a top surface of the device layer **114** to a bottom surface **107** of the trench **105**. The width w of a trench **105** is the distance between the first sidewall **108** and a second sidewall **112** of adjacent angled device structures **106**.

The first sidewall **108** and second sidewall **112** have a reduced sidewall thickness variation. The sidewall thickness variation is the difference between a maximum point and a minimum point on either the first sidewall **108** or the second sidewall **112**. The sidewall thickness variation of the first sidewall **108** and the second sidewall **112** is less than about 20 nm. A reduced sidewall thickness variation may increase the efficiency of the angled device structures **106**, and subsequently the overall performance of the waveguide **100**.

In one embodiment, which can be combined with other embodiments described herein, the device angle γ of two or more angled device structures **106** are different. As shown in FIGS. **1**B and **1**C, the device angle γ of the angled device structure **106** of the first grating **104***a* is different from the device angle γ of the angled device structures of second grating **104***b*. In another embodiment, which can be combined with other embodiments described herein, the device angles γ of two or more angled device structures **106** are the same. The depth d of two or more angled devices structures **106** may be different. In another embodiment, which can be combined with other embodiments described herein, the depths d of two or more angled devices structures **106** are the same. The pitch p of two or more angled devices structures **106** may be different. In another embodiment, which can be combined with other embodiments described herein, the pitches p of one or more angled devices structures **106** are the same.

The substrate **101** may also be selected to transmit a suitable amount of light of a desired wavelength or wavelength range, such as one or more wavelengths from about 100 to about 3000 nanometers. Without limitation, in some embodiments, the substrate **101** is configured such that the substrate **101** transmits greater than or equal to about 50% to about 100% of an IR to UV region of the light spectrum. The substrate **101** may be formed from any suitable material, provided that the substrate **101** can adequately transmit light in a desired wavelength or wavelength range and can serve as an adequate support for the angled device structures **106** (when the angled device structures **106** are formed in the device layer **114**) described herein. Substrate selection may include substrates of any suitable material, including, but not limited to, amorphous dielectrics, non-amorphous dielectrics, crystalline dielectrics, silicon oxide, polymers, and combinations thereof. In some embodiments, which can be combined with other embodiments described herein, the substrate **101** includes a transparent material. Suitable examples may include an oxide, sulfide, phosphide, telluride or combinations thereof. In one example, the substrate **101** includes silicon (Si), silicon dioxide (SiO_2), germanium (Ge), silicon germanium (SiGe), silicon carbide (SiC), titanium oxide (TiO_x), niobium oxide (NbO_x) sapphire, and high-index transparent materials such as high-refractive-index glass.

In some embodiments, which can be combined with other embodiments described herein, the device layer **114** includes, but is not limited to, one or more of silicon oxycarbide (SiOC), titanium dioxide (TiO_2), silicon dioxide (SiO_2), vanadium (IV) oxide (VOx), aluminum oxide (Al_2O_3), aluminum-doped zinc oxide (AZO), indium tin oxide (ITO), tin dioxide (SnO_2), zinc oxide (ZnO), tantalum

pentoxide (Ta_2O_5), silicon nitride (Si_3N_4), zirconium dioxide (ZrO_2), niobium oxide (Nb_2O_5), cadmium stannate (Cd_2SnO_4), or silicon carbon-nitride (SiCN) containing materials. In some embodiments, which can be combined with other embodiments described herein, the material of the device layer **114** may have a refractive index between about 1.5 and about 2.65. In other embodiments, which can be combined with other embodiments described herein, the material of the device layer **114** may have a refractive index between about 3.5 and about 4.0.

FIG. **2** is a schematic, side view of an angled etch system **200**. It is to be understood that the angled etch system **200** described below is an exemplary angled etch system and other angled etch systems may be used with or modified to fabricate the waveguides **100** having angled device structures **106** in accordance with the embodiments of the disclosure.

The angled etch system **200** includes an ion beam chamber **202**. A power source **204**, a first gas source **206**, and a second gas source **208** are coupled to the ion beam chamber **202**. In one embodiment, which can be combined with other embodiments described herein, the power source **204** is a radio frequency (RF) power source. The first gas source **206** is in fluid communication with the interior volume **205** of ion beam chamber **202**. The first gas source **206** is an inert gas source which supplies an inert gas, such as argon, hydrogen, or helium, to the ion beam chamber **202**. The second gas source **208** is in fluid communication with the interior volume **205** of ion beam chamber **202**. The second gas source **208** is a process gas source which supplies a process gas to the ion beam chamber **202**. The process gas includes, but is not limited to, one or more of a chlorine containing gas, a fluorine containing gas, a bromine containing gas, an oxygen containing gas, a silicon containing gas, a nitrogen containing gas, a hydrogen containing gas, or the like. In the embodiments of the method **300** described herein, which can be combined with other embodiments described herein, two or more process gases may be utilized.

A first process gas may have a substrate etch chemistry that is selective to a hard mask material. The etch selectivity of the first process gas having the substrate etch chemistry provides for a selectivity of the substrate material to the hard mask material (described below) of about 5:1 or greater. The etch selectivity of the first process gas having the device material etch chemistry provides for a selectivity of the device material to a hard mask material of about 5:1 or greater. In one embodiment, which can be combined with other embodiments described herein, the substrate etch chemistry includes a chlorine containing gas, a fluorine containing gas, or a combination thereof. In another embodiment, which can be combined with other embodiments described herein, the device material etch chemistry includes the chlorine containing gas, the fluorine containing gas, or the combination thereof.

A second process gas may have a hard mask etch chemistry that is selective to the substrate material or device material. The etch selectivity of the second process gas having the hard mask etch chemistry provides for a selectivity of the hard mask material to the substrate material of about 10:1 or greater or a selectivity of the hard mask material to the device material of about 10:1 or greater. In one embodiment, which can be combined with other embodiments described herein, the hard mask etch chemistry includes oxygen gas (O_2) and carbon tetrafluoride (CF_4). In another embodiment, which can be combined with other embodiments described herein, the hard mask etch chemistry includes argon gas (Ar), nitrogen gas (N_2), and hydrogen gas (H_2). In yet another embodiment, which can be combined with other embodiments described herein, the hard mask etch chemistry includes nitrogen gas (N_2) and hydrogen gas (H_2).

In operation, a plasma is generated in the ion beam chamber **202** by applying RF power via the power source **204** to the inert gas and the process gas provided to the interior volume **205** of ion beam chamber **202** to generate a plasma. Ions of the plasma of the inert gas and the process gas are extracted through an aperture **210** of an extraction plate **212** to generate an ion beam **216**. The aperture **210** of the ion beam chamber **202** is operable to direct the ion beam **216** at an angle α relative to a datum plane **218** oriented normal to the substrate **101** (i.e., the surface normal s). The ion beam **216** includes, but is not limited to, a spot beam, a ribbon beam, or a full substrate-size beam. The ion beam **216** generated includes one of the substrate etch chemistry, the device material etch chemistry, or the hard mask etch chemistry dependent on the process gas utilized.

The substrate **101** is retained on a platen **214** coupled to a first actuator **219**. The first actuator **219**, which may be a linear actuator, a rotary actuator, a stepper motor, or the like, is configured to move the platen **214** in a scanning motion along a y-direction and/or a z-direction. In one embodiment, which can be combined with other embodiments described herein, the first actuator **219** is further configured to tilt the platen **214** such that the substrate **101** is positioned at a tilt angle β relative to the x-axis of the ion beam chamber **202**. The angle α and tilt angle β result in a beam angle ϑ relative to the datum plane **218** normal to the substrate **101**. A second actuator **220** may also be coupled to the platen **214** to rotate the substrate **101** about the x-axis of the platen **214**.

FIG. **3** is a flow diagram of a method **300** for forming waveguide structures. A plurality of angled device structures **106** formed using method **300** are shown in FIGS. **4**A-**4**E. FIGS. **4**A-**4**C are schematic, cross sectional views of a substrate **101** during the method **300**. FIGS. **4**D-**4**E are schematic, top views of the substrate **101** during the method **300**.

To facilitate explanation, the method **300** will be described with reference to the angled etch system **200** of FIG. **2**. However, it is to be noted that angled etch systems other than the angled etch systems described herein may be utilized in conjunction with method **300**. In one embodiment, which can be combined with other embodiments described herein, the portion **401** may correspond to a portion or a whole surface of the substrate **101** of a flat waveguide **100** to have the plurality of angled device structures **106** formed thereon. In another embodiment, which can be combined with other embodiments described herein, the portion **401** may correspond to a portion or a whole surface of the substrate **101** of a waveguide combiner to have the plurality of angled device structures **106** formed thereon. The portion **401** may correspond to one or more gratings **104**. While FIGS. **4**A-**4**E depict etching the substrate **101** such that the angled device structures **106** are disposed in the substrate **101**, a device layer **114** (as described above) may be disposed on the top surface **103** of the substrate **101** such that the angled device structures **106** are disposed in the device layer **114**.

At operation **301**, as shown in FIG. **4**A and FIG. **4**D, a substrate **101** is positioned at a first rotation angle ϕ_1. The first rotation angle ϕ_1 is defined with respect to datum line **402**, as shown in FIG. **4**D. In one embodiment, which may be combined with other embodiments described herein, the first rotation angle ϕ_1 is 0° defined by datum line **402**. The substrate **101** or the device layer **114** (not shown) includes

a patterned resist layer **404** disposed thereon. The pattern resist layer **404** includes a hard mask that is patterned into a plurality of hard mask structures **407** disposed over the surface **103** of substrate **101**. The hard mask material of the patterned resist layer **404** is selected based on the substrate etch chemistry (in embodiments in which the substrate **101** is etched to form the angled device structures **106**) or the device material etch chemistry (in embodiments in which the device layer **114** is etched to form the angled device structures **106**). In one embodiment, the hard mask material is a photosensitive material such that the patterned resist **404** may be patterned by a lithography process, such as photolithography or digital lithography, or by a laser ablation process to form the plurality of hard mask structures **407**. In one embodiment, the hard mask material is an imprintable material that the patterned resist **404** may be patterned by a nanoimprint process to form the plurality of hard mask structures **407**. In another embodiment, which may be combined with other embodiments described herein, the hard mask material is a hard mask material and the patterned resist **404** is patterned via one or more etch processes to form the plurality of hard mask structures **407**. In yet another embodiment, which may be combined with other embodiments described herein, the patterned resist **404** is an optical planarization layer.

Each hard mask structure **407** has a width **422** from the first sidewall **409** to the second sidewall **411** of the hard mask structure **407**. A plurality of gaps **418** are defined by adjacent hard mask structures **407**. Each of the gaps **418** has a linewidth **420** between the first sidewall **408** and the second sidewall **412** of adjacent hard mask structures **407**.

At operation **302**, as shown in FIG. **4**B and FIG. **4**C, the substrate **101** or device layer **114** is exposed to the beam **416** at the first rotation angle ϕ_1. The substrate **101** or device layer **114** is exposed to the beam **416** at the beam angle ϑ relative to the surface normal of the substrate **101** while positioned at the first rotation angle ϕ_1. In one embodiment, which can be combined with other embodiments described herein, the beam angle ϑ is about 10 degrees to about 80 degrees relative to the surface normal of the substrate **101**. The beam **416** has the substrate etch chemistry or device layer etch chemistry that is selective to the hard mask material, i.e., exposed portions of the substrate **101** or exposed portions of the device layer **114** (not shown) are removed at a higher rate than the hard mask material. The beam **416** etches the exposed portions of the substrate **101** or device layer **114** (as shown in FIG. **4**B) to form a partial trench **405**. The partial trench **405** has a portion of the depth d of the trenches **105** corresponding to the angled device structures **106**. In some embodiments, the whole depth d of the trench **105** may be formed at operation **302**. Each partial trench **405** includes a first sidewall **408** and a second sidewall **412**.

The angled device structure **106** (e.g., the first sidewall **108** and second sidewall **112**) has a device angle γ. The device angle γ may be between about 0° to about 80°, as defined above. In one embodiment, which can be combined with other embodiments described herein, the device angle γ of two or more angled device structures **106** are different. As shown in FIG. **4**B, the device angle γ of the angled device structures **106** of the first grating **104***a* is different from the device angle γ of the angled device structures **106** of the second grating **104***b*. In another embodiment, which can be combined with other embodiments described herein, the device angle γ of two or more angled devices structures **106** are the same.

At operation **303**, substrate **101** is rotated to a second rotation angle ϕ_2. The second rotation angle ϕ_2 is defined with respect to the datum line **402**, as shown in FIG. **4**E. In one embodiment, which can be combined with other embodiments described herein, the platen **214** retaining substrate **101** is rotated to the second rotation angle ϕ_2. In another embodiment, which can be combined with other embodiments described herein, the second rotation angle ϕ_2 corresponds to between about −20° (340°) to about 20° relative to datum line **402**, such as about −10° (350°) to about 10°, such as about −7° (353°) to about 7°. The rotating of the substrate **101** is not limited to a rotation angle ϕ corresponding to −20° to about 20°, but may correspond to any predetermined angle ϕ. In one embodiment, which can be combined with other embodiments described herein, the beam **416** will remain at a beam angle ϑ relative to a datum plane **218** oriented normal to the substrate **101** (i.e., the surface normal s) throughout method **300**. The constant beam angle allows for the throughput to increase because there will not be a need to reconfigure the beam angle ϑ. In one embodiment, which can be combined with other embodiments described herein, the method **300** described herein uses only one angled etch system **200** and requires the hard mask material to only be patterned once to provide for high volume production capability.

At operation **304**, the substrate **101** or the device layer **114** is exposed to the beam **416** at the second rotation angle ϕ_2. The beam **416** etches the first sidewall **408** and the second sidewall **412** of the partial trench **405** to remove roughness and hard mask material in the partial trench **405**. The substrate **101** or the device layer **114** is exposed to the beam **416** at the beam angle ϑ while positioned at the second rotation angle ϕ_2. In one embodiment, which can be combined with other embodiments described herein, the beam angle ϑ is about 10 degrees to about 80 degrees relative to the surface normal of the substrate **101**.

The beam **416** at the second rotation angle ϕ_2 etches the first sidewall **408** and second sidewall **412** to remove roughness and hard mask material in the partial trench **405**. The removal of the roughness and hard mask material in the partial trench **405** may reduce a sidewall thickness variation of the first sidewall **408** and the second sidewall **412**. During operation **302**, roughness on the edges of the hard mask structures **407** may create sidewall thickness variation in the partial trench **405** or the trench **105**. Exposure to the beam **416** may cause portions of the hard mask structures **407** to break from the hard mask structures **407**. The hard mask structure portions may deposit in the partial trench **405** or the trench **105**, creating further sidewall thickness variation. In addition, the deterioration of the hard mask structures **407** may decrease the ability of the hard mask structures **407** to effectively mask the substrate **101** or device layer **114**. The sidewall thickness variation is the difference between a maximum point and a minimum point on either the first sidewall **108** or the second sidewall **112**. The change in the rotation angle exposes different areas of the partial trench **405** to the beam **416**, leading to a reduction in the sidewall thickness variation. The beam **416** at the second rotation angle ϕ_2 reduces the sidewall thickness variation of the first sidewall **108** and the second sidewall **112** to less than about 20 nm. The second rotation angle ϕ_2 etches the first sidewall **408** and the second sidewall **412** while maintaining the device angle γ of the angled device structure **106**.

The substrate **101** may be rotated to one or more additional rotation angles, e.g., a third rotation angle ϕ_3. The substrate **101** or the device layer **114** may be exposed to the beam **416** at the third rotation angle ϕ_3. The third rotation

angle ϕ_3 corresponds to between about −20° (340°) to about 20° relative to datum line **402**, such as about −10° (350°) to about 10°, such as about −7° (353°) to about 7°. The substrate **101** may be rotated in a direction of rotation opposite from a direction of rotation of the second rotation angle ϕ_2. The third rotation angle ϕ_3 may be equal and opposite to the second rotation angle ϕ_2 with regard to the first rotation angle ϕ_1, e.g., the second rotation angle ϕ_2 is 7° and the third rotation angle ϕ_3 is −7° (353°) with regard to the first rotation angle ϕ_1. The beam **416** etches the first sidewall **408** or the second sidewall **412** to further remove roughness and hard mask material in the partial trench **405**. The substrate **101** or device layer **114** is exposed to the beam **416** at the beam angle ϑ relative to the surface normal of the substrate **101** while positioned at the third rotation angle ϕ_3. The change in the rotation angle exposes different areas of the partial trench **405** to the beam **416**, leading to a reduction in the sidewall thickness variation. The third rotation angle ϕ_3 etches the first sidewall **408** and the second sidewall **412** while maintaining the device angle γ of the angled device structure **106**.

The substrate **101** may be repeatedly processed according to operations **301-304** to achieve the desired sidewall thickness variation. Operations **301-304** may be repeated from 1 cycle to about 100 cycles to form the trench **105**. During each cycle, a portion of the depth d of the trench **105** may be etched. Each cycle etches a portion of the substrate **101** or the device layer **114** until the desired depth d is achieved. The rotation of the substrate **101** from the first rotation angle ϕ_1 to the second rotation angle ϕ_1 allows for the removal of roughness and hard mask material from the first sidewall **408** and second sidewall **412** of the partial trench **405**. In some embodiments, the substrate **101** may be rotated from the second rotation angle ϕ_2 to the third rotation angle ϕ_3 to further remove roughness and hard mask material from the first sidewall **408** and second sidewall **412**. The rotation from the first rotation angle ϕ_1 to the second rotation angle ϕ_2 and to the third rotation angle ϕ_3 allows for the roughness and hard mask material to be removed while maintaining the device angle γ of the angled device structure **106**.

At operation **305**, the hard mask structures **407** are removed. The hard mask structures **407** are exposed to the beam **416** at the beam angle ϑ. The beam **416** has a chemistry corresponding to the hard mask etch chemistry so that the ions or electrons will only substantially etch the hard mask structures **407** during the hard mask etch process. The hard mask etch chemistry is selective to the substrate **101** or device layer **114**, i.e., the hard mask structures **407** are removed at a higher rate than the device layer **114** or substrate **101**.

In summation, methods of forming waveguide structures are described herein. The methods utilize rotation of a substrate to have the angled device structures formed thereon. The method removes hard mask material from the trench and reduces the sidewall thickness variation of the angled device structures by rotating the substrate from a first rotation angle to one or more additional rotation angles. The rotation of the substrate exposes portions of the angled device structures to the ion beam in order to remove the hard mask material from the trench and reduce the sidewall thickness variation while maintaining the device angle γ of the angled device structure **106**. The constant beam angle allows for the throughput to increase because there will not be a need to reconfigure the beam angle ϑ. The angled device structures can have different device angles without requiring additional processing systems or changes to etch angles.

While the foregoing is directed to embodiments of the present disclosure, other and further embodiments of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. A method for forming a waveguide, comprising:
positioning a substrate at a first rotation angle relative to a datum line of the substrate, the first rotation angle selected to form one or more angled device structures with a first device angle relative to a vector parallel to the substrate;
exposing the substrate to an ion beam, the ion beam configured to contact the substrate at an beam angle ϑ relative to a surface normal of the substrate;
forming first trenches defined by adjacent angled device structures with the first device angle;
rotating the substrate to a second rotation angle relative to a datum line, wherein the second rotation angle is from about −20° to about 20°;
exposing the substrate to the ion beam;
removing a roughness and a hard mask material from a sidewall of the first trenches using the ion beam; and
repeating the method from about 1 cycle to about 100 cycles to form a plurality of trenches defined by adjacent angled device structures.

2. The method of claim **1**, wherein the trenches in the plurality of trenches have a first sidewall and a second sidewall, the first sidewall and the second sidewall having a sidewall thickness variation of less than about 20 nm.

3. The method of claim **1**, wherein the second rotation angle is different from the first rotation angle.

4. The method of claim **1**, further comprising forming a plurality of second trenches defined by adjacent angled device structures with a second device angle.

5. The method of claim **4**, wherein the second device angle is different from the first device angle.

6. The method of claim **1**, wherein a device layer is disposed over the substrate such that the one or more angled device structures are formed in the device layer.

7. The method of claim **1**, further comprising a patterned resist disposed over the substrate, the patterned resist having a plurality of hard mask structures, wherein adjacent hard mask structures define gaps to expose the substrate.

8. A method for forming a waveguide, comprising:
positioning a substrate at a first rotation angle relative to a datum line of the substrate, the first rotation angle selected to form one or more angled device structures with a first angle relative to a vector parallel to the substrate;
exposing the substrate to an ion beam, the ion beam configured to contact the substrate at a beam angle ϑ relative to a surface normal of the substrate;
forming a trench defined by adjacent angled device structures, the trench having a first sidewall and a second sidewall;
rotating the substrate to a second rotation angle relative to the datum line, wherein the second rotation angle is from about −20° to about 20°;
exposing the substrate to the ion beam;
removing a roughness and a hard mask material from a sidewall of the trench using the ion beam;
rotating the substrate to a third rotation angle relative to the datum line, wherein the third rotation angle is from about −20° to about 20°;
exposing the substrate to the ion beam;

removing the roughness and the hard mask material from a sidewall of the trench using the ion beam; and

repeating the method from about 1 cycle to about 100 cycles to form a plurality of trenches defined by adjacent angled device structures.

9. The method of claim **8**, wherein the second rotation angle is different from the third rotation angle.

10. The method of claim **8**, wherein a sidewall thickness variation of the first sidewall and the second sidewall is less than about 20 nm.

11. The method of claim **8**, wherein the third rotation angle is from about −10° to about 10°.

12. The method of claim **8**, wherein a device layer is disposed over the substrate such that the one or more angled device structures are formed in the device layer.

13. The method of claim **8**, further comprising a patterned resist disposed over the substrate, the patterned resist having a plurality of hard mask structures, wherein adjacent hard mask structures define gaps to expose the substrate.

14. A method for forming a waveguide, comprising:

positioning a substrate at a first rotation angle relative to a datum line of the substrate, the first rotation angle selected to form one or more angled device structures with a first angle relative to a vector parallel to the substrate, the substrate having a patterned resist disposed thereon, the patterned resist comprising:

a plurality of hard mask structures; and

one or more gaps, each of the gaps defined by adjacent hard mask structures;

exposing the substrate to an ion beam, the ion beam configured to contact the substrate at an beam angle ϑ relative to a surface normal of the substrate;

forming a trench defined by adjacent angled device structures, the trench having a first sidewall and a second sidewall, wherein the trench is formed using the ion beam having a substrate etch chemistry to remove the substrate;

rotating the substrate to a second rotation angle relative to the datum line, wherein the second rotation angle is from about −20° to about 20°;

exposing the substrate to the ion beam;

removing the roughness and the hard mask material from a sidewall of the trench using the ion beam; and

removing the hard mask structures, wherein the hard mask structures are removed by the ion beam generated by a hard mask etch chemistry different than the substrate etch chemistry.

15. The method of claim **14**, wherein a sidewall thickness variation of the first sidewall and the second sidewall is less than about 20 nm.

16. The method of claim **14**, wherein the second rotation angle is different from the first rotation angle.

17. The method of claim **14**, further comprising:

rotating the substrate to a third rotation angle relative to the datum line, wherein the third rotation angle is from about −20° to about 20°;

exposing the substrate to the ion beam; and

removing the roughness and the hard mask material from the sidewall of the trench using the ion beam.

18. The method of claim **17**, wherein the third rotation angle is different from the first rotation angle and the second rotation angle.

19. The method of claim **14**, wherein a device layer is disposed over the substrate such that the one or more angled device structures are formed in the device layer.

20. The method of claim **19**, wherein the angled device structures are formed using the ion beam having a device layer etch chemistry to remove the device layer.

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